ADVANCED CHT SIMULATIONS FOR BRAKE DISC COOLING APPLICATIONS USING ICONCFD

Rene Devaradja, Christian Taucher, Jacques Papper,
ICON Technology & Process Consulting GmbH
Neuer Wall 50
20354, Hamburg
r.devaradja@iconcfd.com, c.taucher@iconcfd.com, j.papper@iconcfd.com

Christopher Hantschke
Wheel Brake Development
AUDI AG
85045, Ingolstadt
christopher.hantschke@audi.de

Abstract: Thermal analysis of complete brake systems poses a significant computational challenge due to the complex physical phenomena involved, including transient Conjugate Heat Transfer (CHT), radiation, rotating meshes, and the necessity for fine grids to resolve the internal ventilation within the brake disc. The escalating turnaround times per simulation have led ICON to devise a streamlined simulation process, tailored for industrial applications, that combines simplicity, speed, accuracy, and robustness. The primary objective of this process is to deliver precise temperature predictions for the brake system and its immediate environment during the cool-down phase.

A new thermal model has been developed to facilitate the description of inter-region heat exchange occurring over a rotating surface whilst using a static mesh. This model, based on the Band-Averaged Flux (BAF) method first introduced by the authors in [1] and [2], is applicable under high rotor speed conditions. It is grounded upon the fundamental assumption that the thermal diffusion time scale of the brake disc is significantly larger than the rotation time scale, a premise that holds true for vehicles moving at a speed of 50 km/h or more.

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AUDI AG has emerged as an early adopter of this innovative process, collaborating closely to refine and implement the methods effectively. This industrial partnership has yielded a wealth of experimental data, enabling rigorous validation of the computational model. In this paper, we will present the application of the BAF model in industrial cases. We will discuss both the merits and limitations inherent to this methodology and show that it allows efficient and precise predictions of transient cool-down rates of complex brake disc designs throughout the vehicle development process.

1 Introduction

In recent decades, CFD simulations have been extensively utilized in the realm of design assessment and optimization. The accessibility of External Aerodynamics (EA) simulations has notably increased, necessitating only a few hours of training for novices to embark on these tasks. Nonetheless, delving into more intricate challenges, such as the complex thermal phenomena entwined with rotating components like brake disc rotors, underlines the need for the proficiency of seasoned simulation experts when configuring and executing these simulations.

ICON provides an effective solution through its iconPlatform simulation cloud [3] which empowers experts to methodically configure the simulation environment. Subsequently, product designers working on specific projects can readily harness these pre-configured setups. Within the framework of iconPlatform, these tailored configurations are denoted as "Apps". Each App serves a precise purpose, encapsulating industrial best practices and domain expertise, thus ensuring a consistent setup, and streamlining post-processing activities.

2 Brake Cooling Application

A dedicated App has been developed to enable the simulation of brake cooling under constant drive speed conditions. This specialized App incorporates a distinct methodology geared towards achieving a precise geometric representation of the brake system containing a multitude of components with heterogeneous sizes. Furthermore, it enables accurate modelling of heat transfer within such systems, encompassing thermal convection in the surrounding air, conduction within the solid components, and radiation. To enhance usability, all results generated are automatically post-processed, allowing the end user to analyse the thermal solution effortlessly.

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2.1 Computational Domain

Within the framework of iconCFD®, the automatic hex-dominant grid generator seamlessly meshes both the solid and fluid regions, accommodating their distinctive settings, such as the volume refinement levels or the number of wall layers, in a single and streamlined step. Additionally, it accurately represents interfaces between adjacent regions with conformal surface discretization on both sides of the interfaces, ensuring heat conservation is upheld throughout the solver stage. Figure 1 serves as an illustrative example of this meshing approach, demonstrated in its application to a brake assembly.

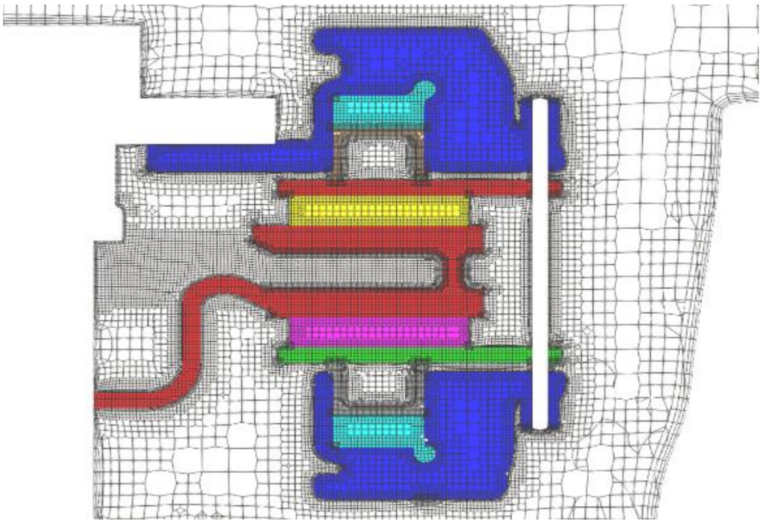

Figure 1: Cross-sectional view of the multi-region fluid-solids mesh.

2.2 Thermal model for rotating solids with geometric angular periodicity

A thermal CHT solver is required to compute heat transfer between the different regions. An additional level of complexity arises in the context of brake systems when it comes to simulate the rotating disc region and its interaction with the surrounding static components. Dynamic mesh solutions may offer the highest level of modelling accuracy, however they come at a substantial computational cost making these simulations impractical.

Instead, an alternative model is described in this section to effectively simulate the thermal interaction between a rotating disc and the external medium, without having to resort to any type of mesh motion technique. This model, previously referred to as BAF, operates under the assumption that a circular distribution of points on a rapidly rotating brake disc encounter the same external environment. This hypothesis allows to establish a fundamental equivalence between the time-averaging of a property that would be calculated using a dynamic mesh approach and the space-averaging of the same property calculated with a static mesh.

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For this equivalence to be valid, the disc must be divided into distinct parts that are physically exposed to the same external heat load, like for instance the inboard and outboard friction surfaces, the internal vanes, etc. Each of these parts is then automatically subdivided into concentric bands of a given thickness. Specific boundary conditions are then invoked to compute heat transfer for each of these bands by evenly balancing the heat fluxes across them. Figure 2 illustrates this concept for one of the internal surfaces of the disc, discretized into several coloured band macros. The same figure also illustrates the resulting heat fluxes, constant per band, on the entire disc solid. The solver finally uses these band-averaged heat fluxes to solve the multi-region heat equation accordingly.

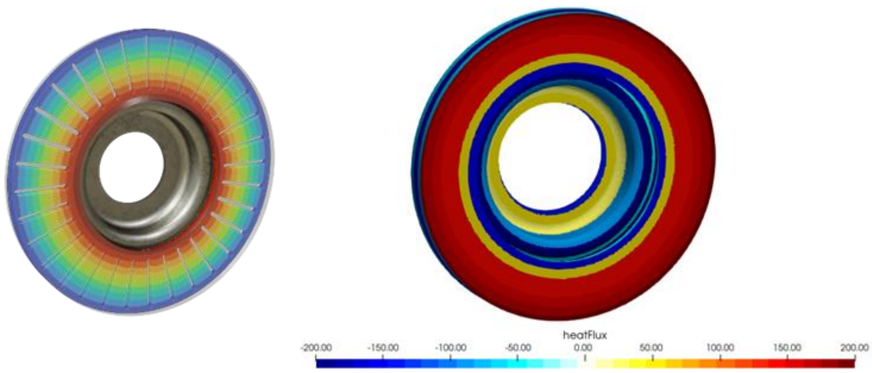

Figure 2: Representation of the internal cooling patch segmented into bands (left) and visualization of calculated heat fluxes per band (right)

The BAF model produces temperature distributions that account for the effects of disc geometric details like vent holes, as depicted in Figure 3. This capability enables engineers to pinpoint hot spots in specific brake disc designs. Additionally, it can be observed that variations in airflow around each side of the disc are reflected in the ranges and contour shapes of temperature.

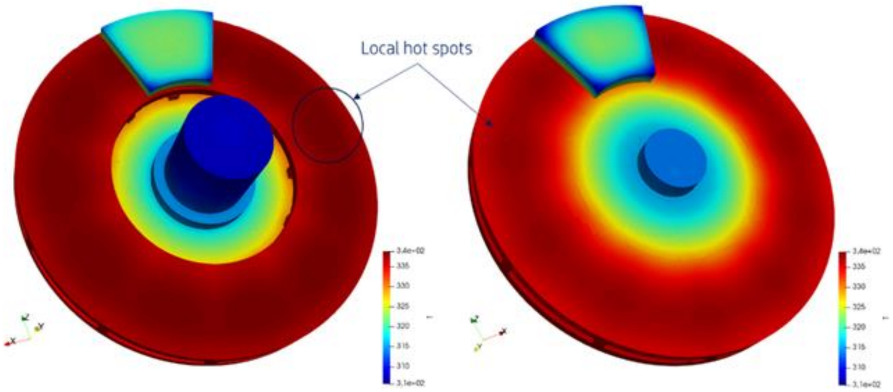

Figure 3: Periodic patterns of temperature distributions obtained with the BAF model

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3 Impact of other physical models

In this section, the importance of physical models involved in thermal analysis for brake cooling is discussed. As the primary goal is to streamline simulations for time efficiency, this often entails simplifying certain aspects of physical models. However, this simplification inevitably leads to approximations in the solutions, subsequently influencing data analysis. It is imperative to maintain a clear understanding of the engineering objectives when selecting the appropriate level of modelling, ensuring that the right balance between efficiency and retention of essential information is satisfied. In this current context, the chosen methodology should provide accurate predictions for the transient evolution of disc temperature during the cooling phase. In addition to the BAF model previously introduced, several other critical choices in physics modelling need to be made when simulating brake cooling. Specifically, models for flow compressibility, air thermal properties, and radiative heat transfer need to be considered. In the following sections, these specific areas are explored and their impact on the results is analysed.

3.1 Flow compressibility

In typical industrial brake cooling simulations, the temperature range spans from approximately 600°C down to 100°C. Given this wide range of temperatures, one might question the necessity of considering compressibility when modelling the airflow. Indeed, if air behaves as a perfect gas, it is important to note that a highly heated brake disc can significantly reduce air density in its immediate vicinity. The reduction in air density leads to a decrease in mass fluxes in that specific region and this, in turn, affects heat convection near the disc's surface.

Figure 4 illustrates the time-dependent evolution of disc temperature for two distinct airflow solutions (note that air flow fields are not updated during the cool-down). Notably, the data reveals that when the air’s density is a function of temperature, the cooling rate of the disc is slower as expected.

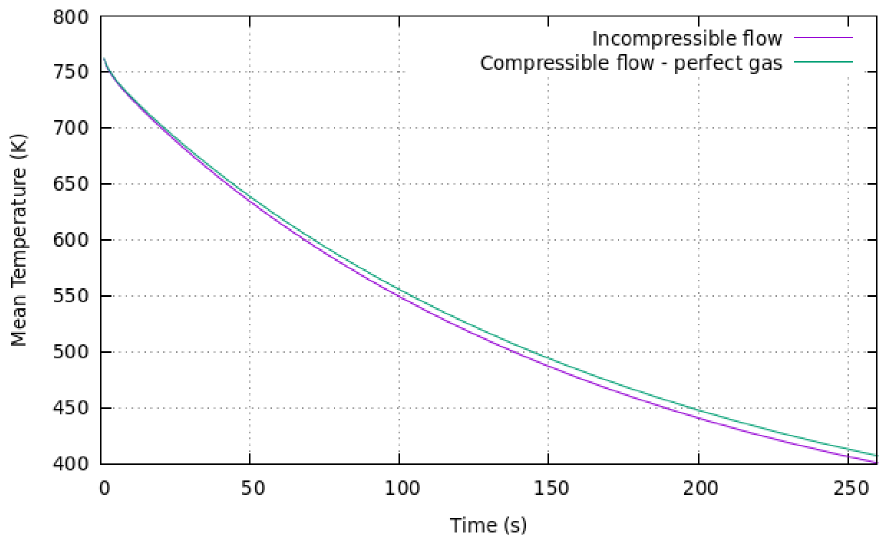

Figure 4: Impact of flow compressibility on brake disc cool-down rate

Even though the two airflows represent the two extreme temperature conditions, their impact on the cool-down curve is relatively small, which in itself justifies the use of a frozen airflow approach in the transient cool-down phase. The choice of flow compressibility is left to the user, however in the cases presented hereafter, the incompressible frozen flow option is selected.

3.2 Air properties

Air properties undergo temperature-dependent variations, with certain properties being more responsive to temperature changes than others. Notably, thermal conductivity can go through a considerable increase as temperature rises. Taking this property into account in the CFD simulations with the Sutherland model can lead to significant modifications in the solution, particularly in areas where heat conduction is the predominant mode of heat transfer. These effects illustrated in Figure 5 can be prominently observed in proximity of any solid wall surface. When activating the Sutherland model, at high temperatures the air thermal conductivity increases changing the graph slope and accelerating the cool-down rate in that region. Naturally, at lower temperatures, the cool-down curves for both models once again run parallel to each other.

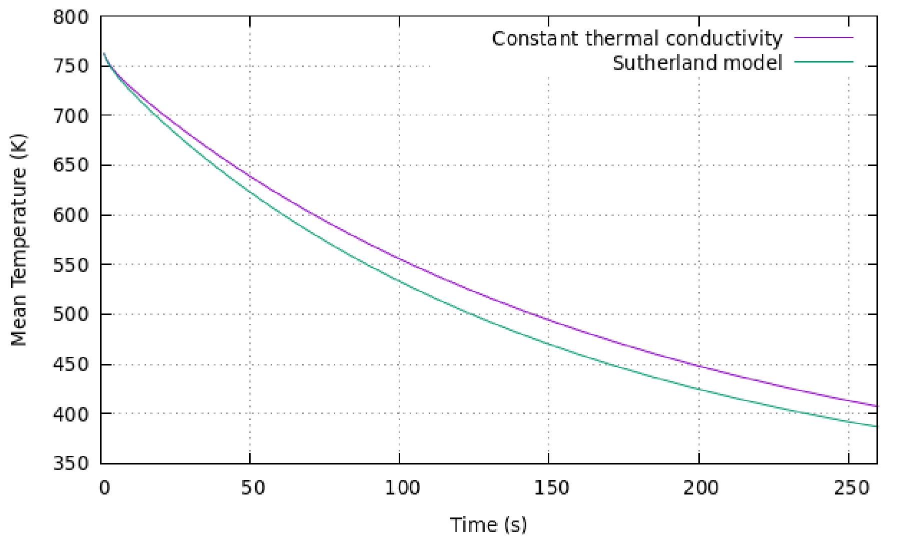

Figure 5: Contrasting brake disc cool-down rates using two distinct thermal conductivity models

3.3 Heat radiation

In the scenario of constant cooling drive, while convection remains the dominant mode of heat transfer, it is essential to recognize that radiation also exerts a noteworthy influence on the disc's cooling rate. To emphasize the impact of radiative heat transfer, a transient cool-down simulation is conducted, comparing cases with and without radiation effects. Initially, a simplified radiation model is employed, which approximates incident radiation on the surface by using a constant infinite reference temperature. Furthermore, a more sophisticated surface-to-surface (S2S) radiation model based on view factors is utilized in order to assess the improvement in accuracy compared to the simplified radiation model. The results of this investigation, as presented in Figure 6, clearly indicate an important heat loss due to radiation when it is integrated into the thermal simulation. Also, as anticipated, the S2S model introduces lower radiation losses owing to its more precise calculation of radiative heat fluxes.

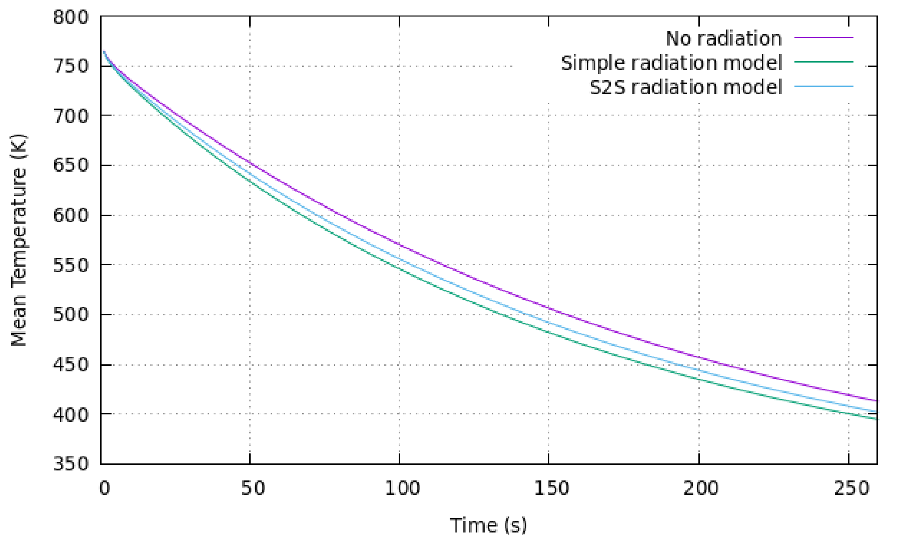

Figure 6: Influence of radiation on brake disc cool-down rate

4 Full vehicle simulation

In this section, the BAF model is integrated into a comprehensive thermal model encompassing a fully detailed car geometry. The simulation approach adopted in this context seeks to evaluate the impact of the vehicle's EA on the cooling efficiency of the brake disc. Consequently, high fidelity geometric representation of relevant parts, including but not limited to wheel arch, rim designs, under-hood details, ride height, must be meticulously considered to ensure an accurate and thorough data comparison.

4.1 Simulation workflow

As demonstrated in Section 3, in the specific scenario of brake cooling under constant drive speed conditions, the compressibility effects within the air region can be considered negligible. Additionally, buoyancy effects resulting from significant temperature variations are assumed to be substantially smaller compared to the effects of forced convection. Consequently, it is justifiable to decouple the EA simulation from the thermal analysis. In this approach, the EA simulation is initially conducted independently, yielding a converged solution without any thermal modelling. This solution is then preserved and held constant during the subsequent thermal simulations (frozen flow approach).

The thermal simulation of brake cooling is divided into two distinct phases. In the first phase, the brake system is subject to a prescribed heat load at the interface between the brake pad and disc solids resulting from friction. This heat load serves the purpose of elevating the temperatures of the materials and initializing the thermal solution for the subsequent cooling phase. During the cool-down phase, the heat release is discontinued, and an air gap is introduced to model the separation between the brake pad and the disc. This arrangement effectively prevents direct heat conduction between these two regions.

This decoupled approach significantly reduces the overall solver runtime when compared to a fully coupled approach. To provide an indication of the time efficiency of the proposed workflow, the runtime for thermal simulations is less than half that of the steady-state primary flow solver employed in the EA simulation.

4.2 AeroSUV Proof-of-concept case

The brake cooling methodology is applied to the AeroSUV geometry [3], which has been modified by ICON to include a brake system on the left wheel. This study investigates three distinct cooling configurations, as depicted in Figure 7 in order to demonstrate the capability of the BAF model to predict the differences in the thermal solution of the brake disc. The first configuration, situated on the left side of Figure 7, represents the baseline setup, wherein no modifications are made to the underbody of the AeroSUV model. In the second configuration, a cooling channel is integrated into the front underbody, designed to direct cold air into the wheel well. Finally, in the third configuration, an additional guide vane is introduced near the steering link. The purpose of this vane is to collect airflow from the cooling ramp and redirect it towards the brake disc rotor's bell, thereby enhancing the cooling process of the disc.

Figure 7: Illustration of brake cooling design on AeroSUV

Examination of the airflow solution for the three different designs is shown in Figure 8 and Figure 9. The baseline case reveals that the upstream flow bypasses the wheelhouse. Consequently, the brake disc is mainly cooled down by the secondary airflow generated through the disc internal blades. With the inclusion of the cooling channel, there is a noticeable redirection of the ambient airflow towards the brake system, leading to an increased mass flow throughput. Finally, with the guide vane in place, the airflow can be directed axially towards the brake disc, further boosting the mass flow rate, and enhancing the cooling process.

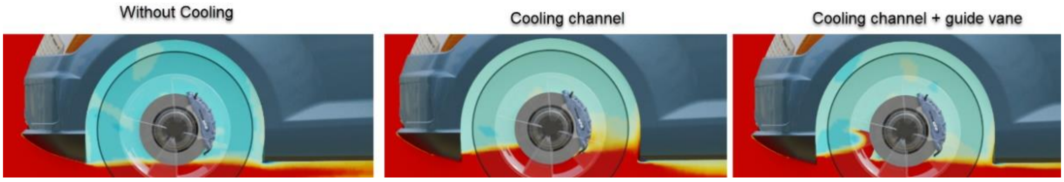

Figure 8: Cross-section of fluid volume with total pressure visualization

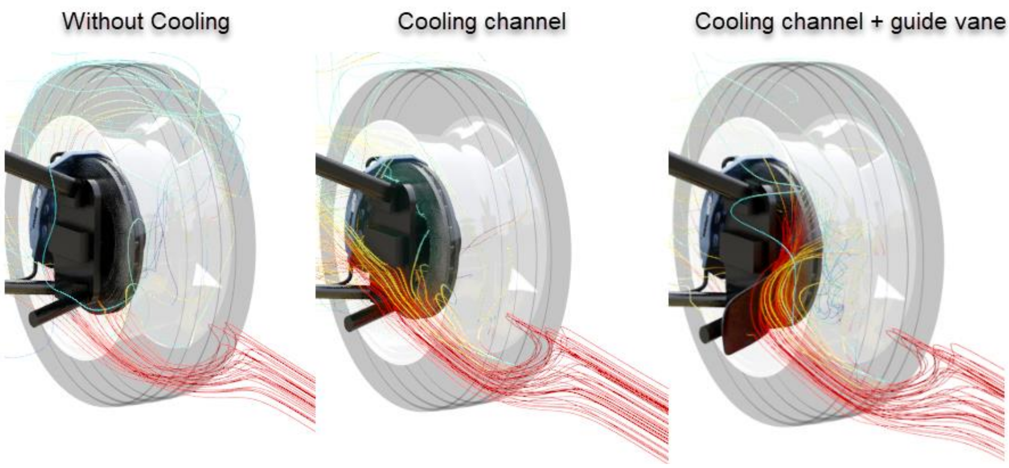

Figure 9: Flow streamlines with total pressure visualization

Figure 10 presents the average material temperature within the brake disc rotor region for the three vehicle variants during the cool-down phase. In the absence of any cooling interventions, the disc requires over 4 minutes and 50 seconds to decrease its temperature from 600°C to 100°C while maintaining a constant vehicle speed of 140 kph. The introduction of wheel house ventilation with cold air reduces this cooling time by 1 minute and 20 seconds. Furthermore, the incorporation of the guide vane results in a further reduction in the cool-down time, bringing it down to 3 minutes. Cumulatively, these measures lead to a reduction in the necessary cool-down time by 1 minute and 50 seconds.

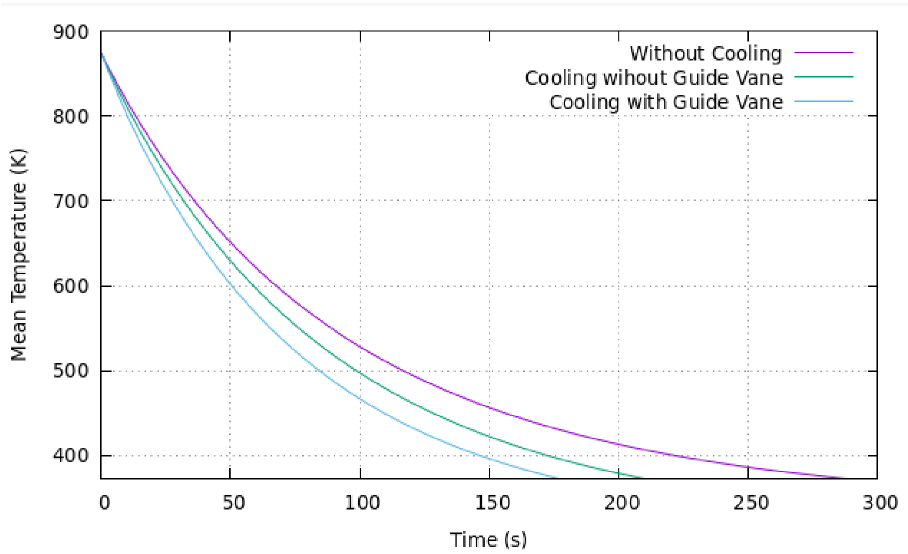

Figure 10: Mean brake disc rotor temperature during cooling phase

Results from this case study show that the BAF model properly accounts for variations in the airflow in the thermal solution of brake cooling simulations.

4.3 Audi Validation Case

In this section, the validation of the BAF model in a real-world case is presented. The vehicle model chosen for validation is a SUV from the Audi model palette, which incorporates detailed geometric features in the under-hood, underbody, and wheel regions.

For this case, the CHT mesh has around 93 million cells. It contains 14 solid regions for the brake assembly and 1 fluid region for air. Face clustering is applied to all wall boundaries for the S2S radiation model, resulting in about 920000 coarse boundary faces. The EA solution is calculated using the steady-state SIMPLEC solver. The utilized turbulence model is two-layer realizable k-epsilon and rotating walls are modelled by the MRF approach.

The primary engineering goal revolves around achieving precise prediction of the cool-down rate for initially hot brake discs while the vehicle maintains a constant speed of 160 km/h. To validate the model, the criterion involves successfully matching the transient temperature evolution measured on both the front left and right brake discs. The experimental data have been acquired using embedded thermocouples placed in the brake discs during on-track testing, with measurements conducted under real road conditions for a duration of five minutes.

It's important to note that the nature of on-track testing, as opposed to more controlled wind tunnel experiments, introduces inherently higher variability of experimental data. On-track testing conditions are less controlled and repeatable due to external factors such as variations in road surfaces, fluctuations in ambient weather conditions, and the influence of various vehicle operational characteristics.

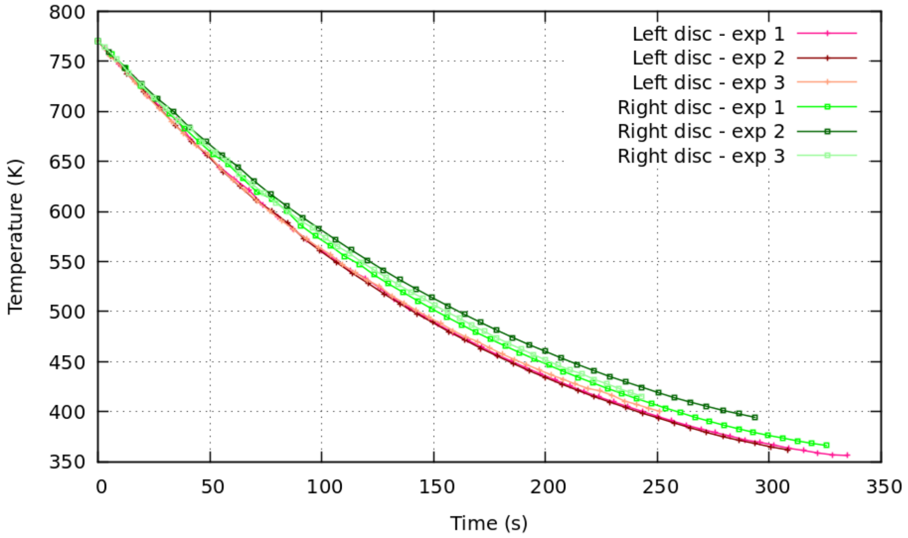

Figure 11 Experimental measurements of cool-down rates for front left and right brake discs

Using the BAF method in conjunction with the S2S radiation model and the Sutherland conductivity model for numerical simulations, the computational results accurately predict the cool-down behaviour for the left disc, as shown in Figure 12.

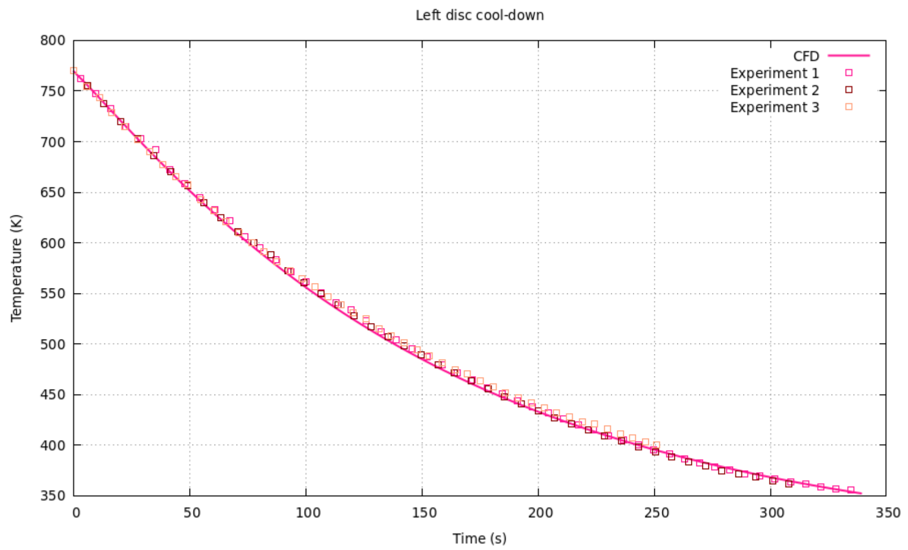

Figure 12 Comparison of cool-down rates for the front left disc

However, for the right disc, our numerical prediction underestimates the cool-down time (see Figure 13).

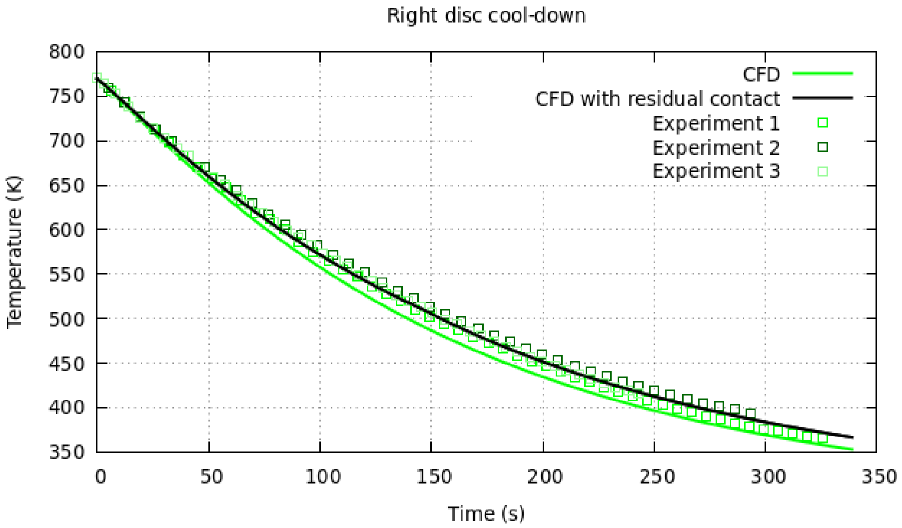

Figure 13 Comparison of cool-down rates for the front right disc

Interestingly, it is worth noting that the cooling curve of that same right disc shows greater spread in measurements in comparison with the left one, as shown in Figure 11. This could indicate the presence of a sensitive transient physical phenomenon in the right wheel arch, which could be difficult to capture with a steady-state airflow solver.

Whereas the collected data reveals a notable difference in the experimental cool-down rates between the left and right brake discs, this is not replicated in the CFD results. Different modelling approaches (e.g. transient DES) for the airflow prediction could be further investigated to help resolve this difference.

Another possible reason for the difference in cool-down observed on the right side may be a residual contact between the pad and the disc which can happen after long braking periods. It was observed that on the prototype vehicle used in the experiment, the pull-back mechanism of the calliper on the front right was not always functioning properly, and thus potentially resulting in this residual contact generating additional heat. Modelling this effect in the CFD simulation results in a better correlation with experiment, as shown in Figure 13.

5 Conclusion

An innovative simulation process has been introduced, providing an efficient tool to explore the performance of brake disc cooling designs. In the realm of thermal modelling for rotating brakes, a novel model based on band-averaged heat flux calculation has been developed and presented. This approach ensures precise predictions of thermal distribution while retaining the use of a static mesh, consequently leading to significant reductions in simulation turnaround times.

Furthermore, we have illustrated the practical utility of this model by employing a generic full vehicle model that incorporates a simplified brake assembly. The outcomes strongly demonstrate the impacts of various cooling devices on brake performance.

A practical case study involving an Audi vehicle demonstrates that precise modelling can effectively align with real-world track data. Joint efforts with AUDI AG have confirmed the reliability of this approach, enabling engineers to enhance the cooling efficiency of brake systems. This method demands only a 50% increase in CPU time compared to a stand-alone EA simulation.

6 Bibliography

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